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A PHASED ARRAY ANTENNA SYSTEM FOR COMMUNICATION SATELLITES

Introduction

The ability to receive and/or transmit information from a satellite through the use of a highly directive antenna pattern can be of prime importance in space communications. A high gain antenna system allows a greater communication range and also provides some discrimination against undesirable electrical interference.

Many techniques and systems have evolved as a means of producing high gain antennas. One approach is the phased array. It is the phased array antenna system which holds such fasinating promise in the satellite communication field. This is particularly true where diversification (nanosecond beam switching, polarization, multi-channel and multi-direction) is a requirement.

It is one matter to impose on a stabilized (e.g. gradient or spin) satellite system the requirement for fixed pointing or near omni-radiation coverage and quite another matter when a satellite must have the ability to point with high gain anywhere in space (4 π steradian coverage). Perhaps the satellite system may impose further the requirement that a capability exist to point in two, three or more directions simultaneously. It is then that considerably more sophistication must be incorporated in communication satellite antenna system design.

[redacted]

The antenna system specialist is aware of these conditions. Several techniques are available which satisfy some of the stated requirements or partially satisfy all the requirements. A new satellite antenna system, sponsored by NASA, Goddard Space Flight Center, has recently been developed and tested. This engineering model is considered probably the most advanced in satisfying the requirements of a truly all, or multi-purpose communication satellite antenna system. It is a multi-beam, high gain, 4π steradians coverage antenna system.

Perhaps, as a clarification or justification of this statement of the capability of this array, a brief, basic description of some phased array antennas is in order. The characteristics of several specific satellite antenna systems will also be mentioned. The theory and hardware description of the multi-beam, 4π steradians coverage antenna systems for communication satellites will be then described.

Basics of Phased Arrays

All phased arrays must satisfy the condition of proper amplitude distribution to the individual elements of the array and the correct relative phase between the elements to achieve beam pointing.

If the n element array of isotropic radiators of Figure 1 is considered the resultant relative field pattern, $E_R(\theta)$, may take the form:

$$E_R(\theta) = E\left[e^{-j\theta\ell} + e^{-j\theta(\ell+\delta_1+\Delta_1)} + e^{-j\theta(\ell+\delta_2+\Delta_2)} + \cdots e^{-j\theta(\ell+\delta_{n-1}+\Delta_{n-1})}\right.$$

where, E is a constant

$\delta_1 = d \sin\theta$, $\delta_2 = 2d\sin\theta$, ---- $\delta_n = (n-1)d\sin\theta$

Δ = phase difference due to feeding.

d = element spacing.

θ = angle relative to array surface.

The direction of propogation then is a function of the electrical spacing between elements and relative phase of the energy fed to the elements. The pattern beamwidth as well as the side lobe level of a particular array of N elements is further dependent upon the amplitude distribution across the arrayed elements (i.e., Gaussian, cosine, cosine squared, etc,).

In the linear phased array block diagram shown in figure 2, $\emptyset_o$, $\emptyset_1$, $\emptyset_2$, ----$\emptyset_n$ represent the required phase correction in each transmission line length to control the beam scan angle. Scanning of the beam by changing the relative phase can be achieved by such means as the biasing of diodes, varactors, etc., or by the application of an electric field to ferrite devices in the RF transmission lines.

The characteristic beam of a linear phased array is such that the beamwidth in the plane containing the elements is a function of the number of elements, the element spacing and the element excitation; whereas the beamwidth in the plane orthogonal to the elements is essentially equal to the beamwidth of a single element. This array is further restricted to scanning in the plane containing the elements and then only to approximately $\pm 45°$ from broadside. At and beyond this scan limit the beam shape rapidly deteriorates and grating lobes become evident.

Phasing radiating elements in linear arrays and in 2 or 3 dimensional arrays, in fact, can be accomplished to provide continuous beam pointing through the scan limits, or it can be phased in discrete steps. The discrete step technique is induced by incremental relative phase shifts or jumps between the elements; hence the result is discrete, overlapping beams.

The incremental phase shift to produce overlapping beams can be accomplished with step (digital) diode phase shifters or through the use of matrix distribution system such as the Butler array technique (figure 3). In the Butler matrix there are N input and N output ports. In the illustrated figure there are eight 8 separate inputs. Each input feeds all eight 8 antenna ports thru fixed phase shifters and power dividers. If RF energy is applied to say, port 2L, the resulting beam thru amplitude and phase distribution in the matrix distribution system would be the second beam to the left of the 0° array axis. The remaining eight 8 beams are similarly produced but have different pointing directions.

Two Dimensional Phased Array

Beam directing techniques in the two orthogonal planes (2 dimensional array) requires the number of components such [illegible] to be comp[illegible]

[illegible] beam pointing [illegible]

[illegible] for a parallel [illegible]

This array may be ana[illegible] manner as [illegible] dimensional or linear ar[illegible] is, the relative [illegible] of [illegible] individual [illegible] must be adjus[illegible]

[illegible]

Phase Shifting Device - The Critical Component

In a steerable phased array antenna system the limiting device is almost always the phase shifter or switch for discrete beam arrays. It is this component that, in many cases, limits the power handling capability and has a strong input on the weight, the power drain and complexity of the antenna array.

Consider the following information. In practice the diode or varactor phase shifter or switch is light, small in size and can switch in nanoseconds using milliwatts of drive power. Its RF power handling is relatively small. As an example a discrete or step phase shifter may handle 20 watts of average power and approximately 1.5 kw peak power in S-band requiring 300 milliwatts of drive power. A step ferrite phase shifter, by comparison, at S-band can handle approximately 500 to 600 watts average power and 70 to 80 kw peak power. Unfortunately, the ferrite device is relatively heavy, large in size and requires in the order of 2½ amps at 30 volts driving power. Furthermore, it suffers from hysteresis effects in addition to being temperature sensitive. The following list may be considered as ideal basic characteristics of phase shifting devices[1]:

1. A minimum phase variation of 360°.
2. The phase setting must be independent of temperature and power level.

3. The insertion loss must be low.

4. The mechanical or electrical inertia should be low to permit phase shifting within the required beam shift interval with the available driving power.

Beam Pointing Requirements as a Function of Satellite Mission and Flight Characteristics.

Since the discussion in this article is confined to communication satellites the specific satellite mission is fixed. But an important consideration as far as the antenna system on a communication satellite is concerned is the satellite's flight characteristics, altitude and attitude. Some of the common satellite orbiting characteristics can be catagorized as one or some combination of:

a. Spin stabilized.

b. Gravity gradient stabilized.

c. Synchronized.

d. Random motion or orientation.

Spin Stabilized

Under the condition of spin stabilization the spin axis of a satellite remains aligned in space per figure 5.

Stabilization condition of figure 5(a) requires a directional antenna beam to point in any direction from the satellite in space to achieve continuous communication with earth. If overall system performance allows relatively small spacecraft antenna gain (±3db nominal) and jamming, either natural or man made, is of no serious consequence then a near omni-antenna pattern coverage would suffice. This could be accommodated with a turnstile type satellite antenna assuming the frequency/diameter of the satellite ratio is a fraction of a wavelength. Another solution is for 2 or more broad pattern antennas to be located on the satellite (with or without switching). Many variations or combinations of antenna elements could be used in phased arrays or single elements.

Now consider the spin stabilized condition of figure 5(b). In this case pattern coverage is necessary only in the plane of the orbit. Adequate pattern coverage can be achieved by radiating energy to form a disk shaped pattern. Or if a more directive antenna pattern is needed a despun antenna can be used. In this latter case a beam is scanned around the satellite in the opposite direction to and at the same rate as the satellite rotation.

Gravity Gradient Stabilization

The gravity gradient type of satellite orientation is illustrated in figure 6. The directional pointing requirements of the antenna system are rather obvious. Again, how much gain in the satellite antenna is required to exhibit is a function of system requirements including satellite range from the earth terminal station. For this condition a phased array with a relatively small scan angle can be used if, indeed, scan is needed.

Synchronized Satellite Stabilization

A synchronized satellite simplifies, somewhat, the requirements imposed upon communication satellite antenna arrays. The satellite remains over a nearly fixed point on earth and at a fixed range for communication system calculations. The satellite can be either spin or gravity gradient stabilized in addition to being synchronous per figure 7 (a), (b), (c). The antenna system depends upon the attitude of the satellite and how well this attitude with respect to earth can be controlled.

The antenna array could be a beam scanning or beam switching type. If necessary a multiple two or three fixed beam array could be used. Again, the directivity of the antenna used is a function of system requirements.

It is possible to use the three synchronized satellite approach where each of three satellites at an altitude of near 19,500 nautical miles above the earth's surface provides coverage of approximately one third of the earth's surface. It is under this last condition that world-wide communication can be obtained. Considerable literature has been written on this high altitude system along with the multiple (50 satellites) random-spaced communication satellite system where these lower altitude satellites (2,200 nautical miles above the earth's surface) are placed in orbit around the earth to achieve world-wide communication.

Random Orientation Satellite

The random variation of satellite-earth orientation or look angles presents quite a challenge to the antenna systems engineer. The random orientation satellite shown in figure 8 is not to be confused with the multiple random spaced satellite system previously mentioned. A possible antenna design to solve this problem is the omni-pattern coverage where the ability to transmit and receive communication is independent of earth satellite orientation. True or complete omni-pattern coverage is not too easily accomplished since some holes or nulls in the pattern will exist in practice. In addition omni-coverage is synonymous with low gain and in some cases may prove inadequate. Another solution would be one in which high gain 4π steradians radiation coverage is achieved, say, thru the use of a multiple beam antenna phased array system.

Finally, with respect to earth-satellite orientation one can conceive of many/ inadvertent combinations of satellite attitude, altitude and motion (spinning, tumbling, coning, etc,). Obviously, control over these parameters is extremely desirable.

Some Phased Array Systems

Some very practical and useful communication satellite phased array techniques have been designed in the past few years which deserve mentioning. No attempt will be made to cover all the operational systems. In general, they fall into one or more of the satellite orientation categories previously described. Only the principles of operation used to achieve their pattern coverage will be discussed along with some of their limitations. Detailed system information is readily available in existing literature.

Syncom Antenna System

The syncom satellite antenna system is an example of a satellite stabilization and an antenna system radiation pattern configured in the most compatible manner. With the satellite in a spin stabilized condition and the spin axis perpendicular to the plane of the orbit per figure 7(b) complete antenna coverage to the earth is provided by a pattern of 6 to 8db gain.

The disk pattern provides omni-azimuth coverage with the pattern in the plane of the orbit. The pattern is formed by a linear array of coaxial slots thereby producing this phased narrow beamwidth in the plane normal to the orbital plane[2]. With the disk shaped pattern produced by the collinear array it must be remembered that a rather strict control of the earth-satellite spin orientation is required. The thinner the "disk-pattern", the more control.

Applications Technology Satellite F-1

This antenna system scans thru 360° in azimuth with a highly directive beam. Briefly, in one form the system is comprised of 16 linearly polarized elements (collinear) arranged in cylindrical fashion shown in plan view in figure 9. The directionally opposed elements are phased in the end fire mode to produce cardioid enveloped patterns similar to that shown. To produce a more directional beam in the specific azimuth shown by the arrow, the cardioid enveloped patterns produced by the paried elements /(1, 9), (2, 8), (3,7), (4,6), (12, 14), (11,15), (10, 16)] and elements 5 and 13 are properly phased. Thus 9 patterns contribute thru proper phasing to the forming of the directional beam in azimuth. It is important to note that elements 5 and 13 must (and do) act independently (i.e., not in the end fire mode) in contributing to the particular azimuth beam direction shown.

No ¶ The phasing is accomplished by ferrite phase shifters.

The array functions at one specific frequency (i.e, narrowband). Beam scanning is not available in elevation.

This beam scanning array could be used in the earth-satellite communication system of relatively high altitude since considerable gain above isotropic (say 18 db) is available. Further, the array scanning capability makes it very attractive for the synchronous missions.

<u>Telstar I Communication Antenna</u>

The Telstar I Communication Antenna System physically formed two belts around the equator of the near-spherical satellite 34.5 inches in diameter[3]. The pattern desired was one which could be produced by a large sphere separated by a gap at the equator. A pattern analysis indicated that an antenna of this type could maintain nearly omni-coverage to within about 20° of the poles of the spherical satellite. The omni-coverage antenna pattern is desirable because of the requirements discussed under spin stabilized satellites earlier.

Unfortunately, because of mechanical problems and thermal gradient problems a simple separation of the two halves of the satellite was not acceptable. Hence, the multi-radiating element approximation of the bisected sphere is used. By placing circularly polarized elements around the equator of the sphere at 0.8λ or less spacing the pattern ripple could be minimized.

One ring array was designed for 6GC (receive) and the other for 4GC (transmit). At 6GC, 72 circularly polarized elements were required to form the array belt and at 4GC, 48 were required (figure 10). Tree-like arrays of hybrids (resistive dividers) were used as the distribution systems to the radiating elements. A reactive power divider was used to feed the segmented groups of resistive power dividers.

Typical patterns for this method of forming a fixed phased array are shown in figure 11.

This phased array antenna system does not scan. The near omni-coverage satisfies system requirement including the satellite flight characteristics of altitude and spin stabilization and therefore the added complexity of a scanning array is avoided.

A 4π Steradian Coverage Phased Array

With the broad brush treatment covering the salient features of phased array patterns for communication satellites completed, the phased array antenna system with multi-purpose communication capability will be described.

A pictorial view of the beam pointing of this phased array is shown in figure 12.

The two 12 element circular aperture planar arrays forms 12 discrete beams each enabling 0° to 45° cone coverage from the axis of the cylindrical satellite. The beams precess around the axis in discrete steps as opposed to orthogonal motion of beams in rectangular or square aperture to achieve coverage equivalent to $2\,[(2-\sqrt{2})\pi]$ steradians.

The 64 element cylindrical array of 16 elements in banks of 4 on the periphery of the cylinder forms beams which cover 360° in azimuth in 16 discrete beams. In addition, at each of the 16 azimuth beam positions the beam scans $\pm 45^\circ$ in elevation in 4 discrete beams. Total coverage for the cylindrical array under this arrangement is $2\sqrt{2}\pi$ steradians.

In total, the capability to cover the complete 4π steradians of space in 88 discrete beams.

Theory of Operation - Cylindrical Array

The geometry of the cylindrical array has always been appealing to system designers because of its ability to provide 360 degrees of coverage. When used as a scanning array, a beam may be swept through 360 degrees by using any of the numerous techniques available for scanning a linear array. When used to provide multiple beams, an array of N elements is excited by N isolated inputs. Each input corresponds to a beam in a selected direction; all of the N beams being disposed uniformly over 360 degrees of azimuth angle. In both the instance of the scanning array and the multiple-beam array, the resolution achieved is comparable to that available from a planar aperture of the same height and with a length equal to that of the cylinder diameter.

In a conventional linear array, each element is controlled in amplitude and phase to achieve a given result. In the cylindrical array, the outputs of each element of an array, having N elements, are processed by a network having N inputs. Each input excites all of the N array elements with equal amplitudes, but with differing phase excitations. These phase excitations are progressive. The increments of phase progression increase from one processing port to the next. The resulting far-field patterns for each of these modes are nearly omnidirectional for the instance where the phase progression between the elements is not large. As the interelement phase progression increases with increasing mode number, the omnidirectivity of the mode deteriorates. When the highest order mode is used, the phase progression between elements is 180 degrees. This type of phase excitation generates an N-lobed amplitude pattern which, because of its special nature, is only useful for multiple-beam applications. The far-field phase pattern of the remaining modes is not uniform with azimuth angle but will vary from zero to $\pm (N - 2) \phi/2$ degrees (where ϕ is the azimuth angle), depending on which input port is excited. The mathematical form of the pseudo omnidirectional patterns, generated by these remaining (N -1) input ports, differs from the mathematical form of the individual elements of a linear array only in the definition of the argument. Since the patterns generated by the inputs of the circular array processing network are of the same form as those used for a linear array, it follows that they may, in turn, be processed by any of the myriad techniques used to process a linear array.

It is important to distinguish between the individual terms used in both cases. In the linear array, the elemental terms represent the contribution of a single radiator in the array. In the cylindrical array, the equivalent elemental terms each represent the equiamplitude progressive phase excitation of all N elements. The distinction between the cylindrical array terms, or modes, is simply the incremental phase difference between each of the N elements.

Figure 13 is a sketch depicting N radiating elements arranged to form a ring in the horizon plane. The spacial orientation of the array, and the physical array parameters denoted in this figure, will be used throughout the remainder of the discussion. The radiation patterns realizable from this type of array may be represented in complex Fourier form as

$$E(\emptyset) = A_o(\emptyset) + A_1(\emptyset)\, e^{j\emptyset} + A_2(\emptyset)\, e^{j2\emptyset} --- A_N(\emptyset) e^{jN\emptyset}, \qquad (1)$$

or more simply in the summation form,

$$E(\emptyset) = \sum_{n=0}^{n=N-1} A_n e^{jn\emptyset}. \qquad (2)$$

In earilier applications, most investigators were only interested in exciting the A_o term to achieve an equiphase, equiamplitude distribution of radiated energy in the $\emptyset$ plane. The imperfections in these patterns, both in phase and amplitude were generally minimized. These imperfections, represented by the remainder of the Fourier terms, generally increased with frequency, thereby limiting the range of frequencies over which a given maximum level of imperfection could be achieved. Later efforts were concerned with the generation of single-lobed patterns. These patterns were indirectly realized by the judicious control of the coefficients A_n. It should be noted, however, that the design procedure was not generally synthesized directly from the Fourier series of equation (1). Early beam-forming methods modified the element phases with line length devices to form a plane wave front and then the element excitation was varied to achieve a given beam shape. Nonetheless, it can be shown that equivalent results could have been achieved by controlling the amplitude coefficients of equation (1).

The idea of synthesizing any beam from a circular array that could be synthesized from a linear array first germinated when the similarity of their basic format was recognized. The general expression for a linear array of N elements may be written directly as

$$E'(\emptyset) = \sum_{n=0}^{n=N-1} A_n e^{jnu} \qquad (3)$$

Where: $E'(\emptyset)$ = the array factor of an array of N linear elements,

N = the number of elements,

A_n = the n^{th} amplitude excitation coefficient,

u = $k\ S \cos \emptyset$,

k = $2\pi/\lambda$,

S = element spacing.

If the comparison between (1) and (3) is limited to one plane, it becomes apparent that the only significant distinction between the two equations is the form of the argument. In the instance of the ring array, the argument is simply $\emptyset$, the azimuth angle. However, in the case of the linear array, the argument is $u = kS\cos\emptyset$. Except for limits then, it follows that the same degree of freedom exists in both cases for synthesizing patterns. The basic problem heretofore with the cylindrical array has been the absence of a technique which would allow separable excitation of the individual terms of equation (1). In the linear array this separable excitation is a simple matter since each term represents the contribution of a single element. In the circular array, the complex spacial arrangement does not allow the individual elements to represent the individual terms of equa tion (1). However, if a method were generated for separately and independently exciting each of the terms of (1), it would follow that the problem of synthesizing beams from a cylindrical array would be no more difficult than synthesizing beams from a linear array.

Some method of exciting all the terms of equation (1) separately and simulteneously is fundamental to the concept of the cylindrical array. The feeding network must excite all of the array elements with equal amplitude for all N input ports. However, the phase progression must vary from one input to another. An N port multiple-beam matrix has this capability. The manner in which this matrix functions has been described in detail in the literature 5, 6, 7 and hence will not be repeated here. The outputs of the multiple-beam matrix are equal in number to the number of elements in the array. The multiple-beam technique generates sidelobes which are theoretically 13 db below the main beam amplitudes. Amplitude tapering techniques presently used in linear arrays for modifying the multiple-beam uniform distribution, can be applied directly to the cylindrical array.

The analysis of the cylindrical array is somewhat unusual in that it does not utilize the conventional approach of computing the far-field pattern from the specific element excitations and the geometry of the array configuration. The described technique utilizes the concept of omnidirectional modes which have the same mathematical format as the contributions of single elements in a conventional linear array. It is then presumed that since the mathematical formats are identical, the types of processing used in each instance would also be identical. This mathematical correlation, although not conventional, is particularly convenient in the instance of the cylindrical array. For example, the derivation of the far-field patterns, and the definition of the excitation coefficients from which these patterns are derived, would be mathematically complex and quite tedious, particularly where multiple-beam systems are being considered.

The cylindrical array technique results in element excitations which, if treated in a conventional manner, would yield the same far-field results. Figure 14 aptly illustrates that this is indeed the case. In the instance shown, the excitations are derived for two types of element patterns: one which is omnidirectional and the other which is a cardioid. In both instances, the far-field pattern could be computed in the normal manner to achieve the same far-field results as is achieved with the above analysis. The character of the excitation coefficients is markedly affected by the element pattern. In the case of an omnidirectional element pattern, the power appearing at the element terminals is equally strong in the direction of the beam pointing and in the reverse direction. For the case where a cardioid pattern is assumed, the energy appears at the element terminal in the direction of the beam pointing, with very little appearing in the reverse direction.

Theory of Operation Twelve-Element Planar Array

This array, as described in the schematic of Figure 15, consists of twelve antenna elements, a twelve-port multiple-beam network, and a SP12T switching network.

The twelve-element planar array is unique in that it does not use the conventional square building block of the more common multiple-beam antenna systems. The array building block for the twelve-element array is a three-element equi-lateral grid. This arrangement allows improved crossover levels to be achieved, while at the same time allowing a reduction in sidelobe levels relative to those obtainable from a conventional square array having the same distribution.

The geometry of the twelve-element multiple-beam array is sketched in Figure 16 and 18. Examination of this figure will indicate that it consists of equi-lateral grids with an element spacing equal to, a. The relative voltage array factor, in any plane containing a row of elements, may be derived as being equal to

$$E_p\ (\psi_p) = \cos\ (\psi/4)\ \frac{\sin\ (3\psi/2)}{\sin\ (4\psi/4)} \qquad (4)$$

where: $\psi_p = k\ a_p \sin\theta$

$a_p = a/2$

a = grid spacing (see figure 16)

$k = 2\pi/\lambda$

θ = angle relative to broadside

λ = wavelength.

The relative voltage array factor for the planes between the rows of elements (see figure 16) may be written as

$$E_m\ (\psi_m) = 5\cos\ (3\psi_m/2) + 7\cos\ (\psi_m/2) + j\ 4\sin\ (\psi_m/2) + \cos^2\ (\psi_m/2) \qquad (5)$$

where: $\psi_m = ka_m \sin\theta$

$a_m = 0.866a$

The array factors derived from equations (4) and (5) are plotted in the sketch of Figure 17. The highest sidelobe is -15.6 db. This sidelobe level may be compared to that of a sizteen-element square array which has a sidelobe level of -11.4 db.

If a multiple-beam twelve-port matrix is utilized, the proper phasors are added in the array factor to generate a cluster of twelve beams. The actual angular location of the patterns can be determined by projecting the ψ-plane patterns on the surface of a sphere. The beam cluster of twelve beams will thus duplicate the element arrangement of the array. The crossover levels can be computed as ranging from -4.1 db between any two adjacent elements, and to -5.0 db at a common crossover of any three elements. By way of comparison, a sixteen-element square array has crossover levels ranging from -3.7 db between any two elements, and to -7.4 db at any crossover common to four elements.

Engineering Model

Using the theory of the cylindrical array and the twelve element planar array described above an engineering model (figure 19) was fabricated demonstrating feasibility of the theory. Following is an explanation of the operation of the engineering model using block diagrams and some pertinent measured characteristics.

Cylindrical Array

The cylindrical array schematic in the form of a block diagram is shown in figure 20. The components are identified and located in their proper position in the system. The linear array formed with typical elements a,b,c and d is a direct application of the Butler matrix discrete beam forming technique. Its function is to allow the elevation scanning of a particular azimuth beam. The phase corrections (η_ϕ) denoted "interposition" indicate the capability to form beams between the four basic matrix beams thus reducing the cross over levels from approximately -4db to about -1 db. To carry this interpositioning scheme one step further it is possible to reduce the cross-over levels of the azimuth discrete beams by incorporating "interposition" switches as indicated between the mode forming and beam forming matrices.

Using the theory previously presented and the distribution network of figure 20, the cylindrical array exhibited the following nominal characteristics.

The measured beamwidth at 2270 Mc is 18° in elevation and 23° in azimuth. The computed gain is then,

$$G \approx 10 \log_{10} \frac{32,500}{\theta_E \, \theta_A}$$

$$G \approx 18.9 \text{ db}$$

where θ_E and θ_A are the beamwidth in elevation and azimuth, respectively. However, the measured gain is 13db. The discrepancy is attributed to system losses in the matrices, switches, cables and spiral radiating elements.

Measured gain of the cylindrical array at 1700Mc is 14.3 db compared to the computed gain of 18.1 db. And in this case also the losses are attributed to the system components.

Twelve Element Planar Array

The schematic - block diagram of the 12 element phased array is illustrated in figure 15. The relative phase of individual radiating elements for one discrete beam pointing direction is denoted on each of the elements of the plan view of the array. Although this particular phased array system scans the upper 45° of a cone in 12 possible choices of beam direction, the incorporation of interposition phase shifters would allow the formation of 12 beams between the 12 original beams thus reducing the cross-over level or ripple to approximately -1 db in the $(2 - \sqrt{2})\pi$ steradians coverage.

The following characteristics of the planar array are nominal. The measured beamwidths are approximately 30° at 1700 Mc and 23° at 2270 Mc. The side-lobe values vary from -18 db to -12 db compared to a -15.6 db computed value. Gain measurements indicate a 14.6 db gain at 1700 Mc and 17 db at 2270 Mc. These gain values are to be compared to the calculated gain of 16.5 db at 1700 Mc and 19.1 db at 2270 Mc. Again, the discrepancy is a result of the system losses (i.e., matrices, switches and cable losses).

Solid State Switches

Beam switching of the array is accomplished by control of bias currents of diodes incorporated into printed circuit hybrids. Thus, the direction of r-f energy flow in the system is changed by the forward or reverse bias of diodes. The switches are considered near optimum in design. Twenty watts of averave RF power handling capability and 1.5 kw peak power allows the antenna system to handle power which is consistent with or exceeds many satellite applications.

Nominal characteristics of the switch are:

(1) VSWR = 1.2:1

(2) Isolation = 24 db

(3) Insertion loss = 0.5 db

(4) Power handling: 20 watts average, 1.5 kw peak

(5) Switching Power (maximum) = 300 milliwatts

System Packaging

In designing this antenna system appropriate consideration was allocated to the packaging of the entire system within what is considered a typical satellite configuration. The system packaging is shown in figure 21. The interior volume of the cylindrical array is essentially open. The weight is 83 lbs including all support members and the cylindrical body housing. Since the antenna system itself forms part of the enclosing structure (i.e., cylinder surface and caps) and the matrices and transmission lines are nearly all printed circuit most of the interior of the satellite is free of obstructions. The weight of the antenna system is approximately 65 pounds.

Conclusion

Antenna pattern coverage requirements for communication satellites under various altitude and attitude conditions have been briefly covered as well as some characteristics of a few practical communication satellite antenna designs.

It is possible to envision the requirement for a communication satellite system which could have the following characteristics:

1. High gain and, hence, some discrimination against undesirable electrical interference.
2. Circular polarization.
3. Frequency bandwidth of 15% to 25%.
4. Ability to receive or transmit in multiple directions either simultaneously (e.g., in a repeater satellite application) or with nanosecond switching time over 4π steradians of space.
5. Kilowatt peak power handling capability.
6. Compact in size.
7. Low drive power for phasing devices.
8. Radiating elements which conform to the diameter of the satellite and thus do not restrict the size to, say, N wavelengths in diameter and/or protrude from the natural contour of the satellite.

As system requirements the items in this list present quite a formidable challenge. Yet, it is believed that the multi-beam 4π steradian coverage satellite antenna system most nearly satisfies these requirements.

To be sure, to use this antenna system for all communication satellites is a mistake. In the previous discussion it has been pointed out which antenna system would solve particular communication satellite "pattern coverage" requirements. Some of these systems are quite simple; some are more complicated. But always, in the interest of cost and reliability, the antenna system used should be that one which will do the job and not necessarily more.

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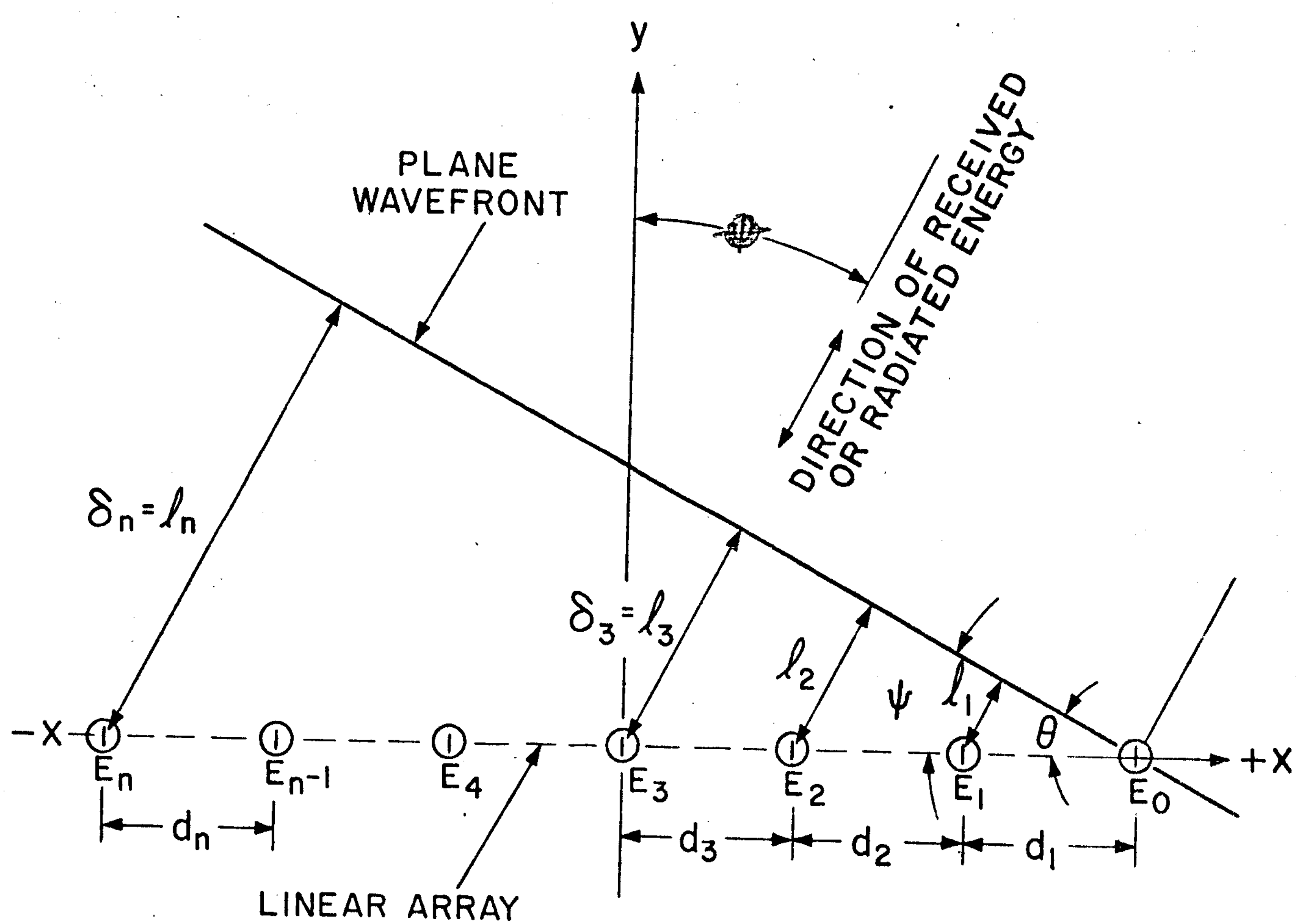


Figure 1—Linear Array Geometry

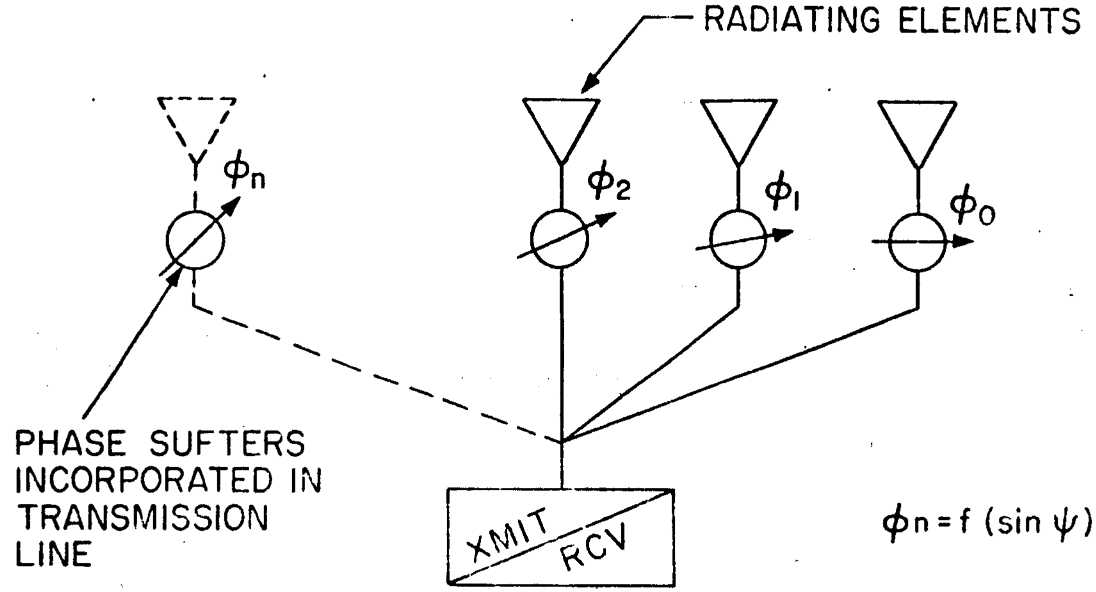


Figure 2 - Linear Array - Phase Shifters

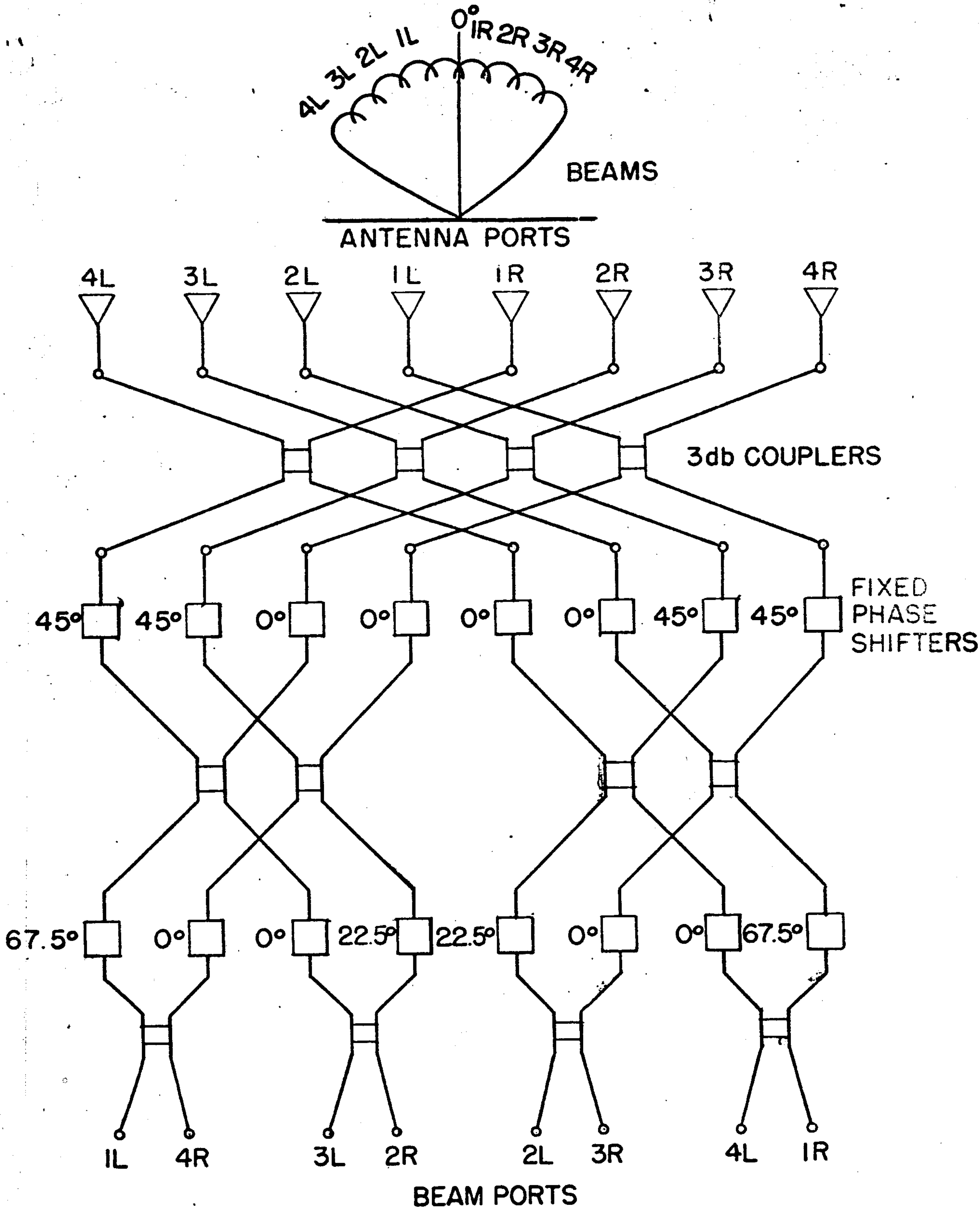


Figure 3 – Butler Matrix

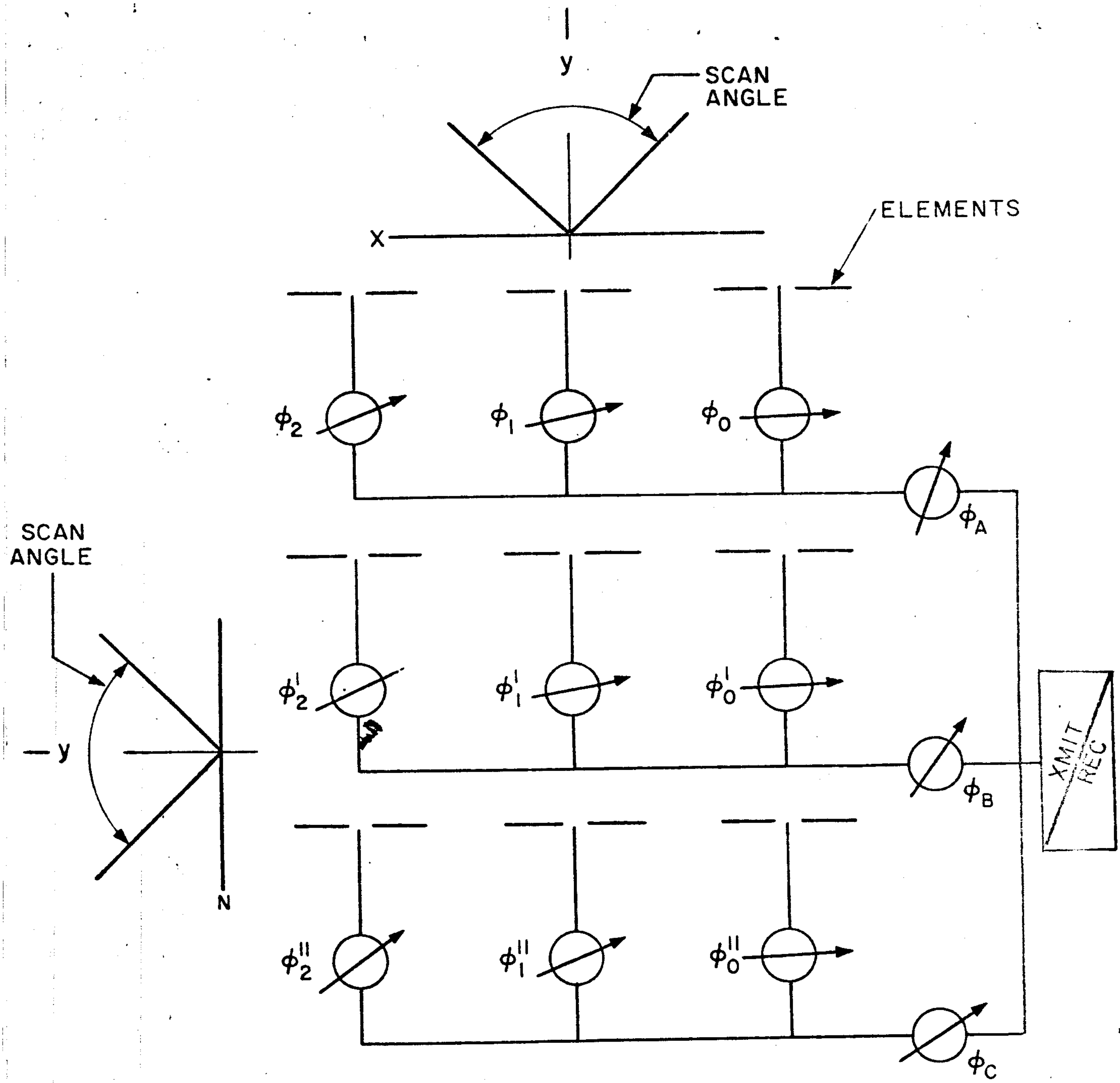
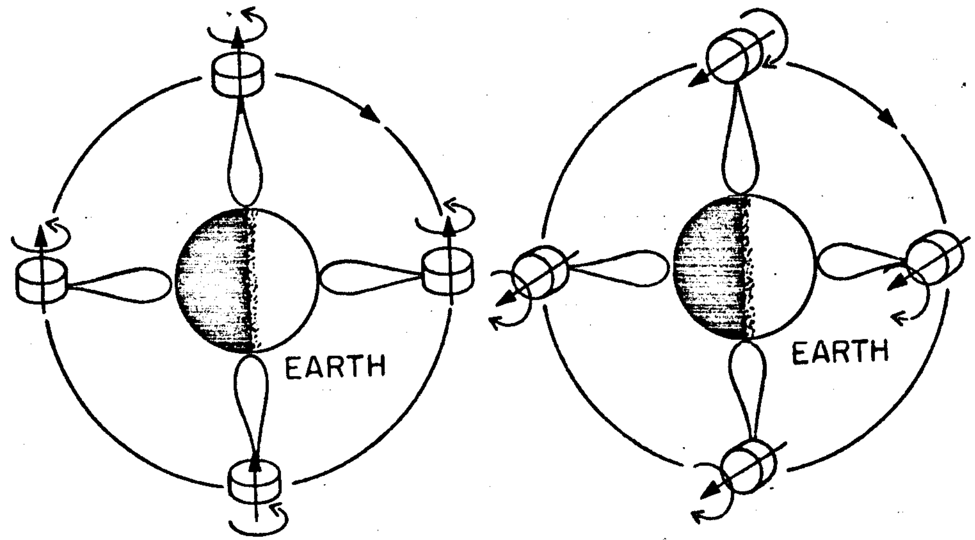


Figure 4 — Two Dimensional Array



(a) Spin axis parallel to orbital plane

(b) Spin axis normal to orbital plane

Figure 5 - Spin Stabilized Satellite

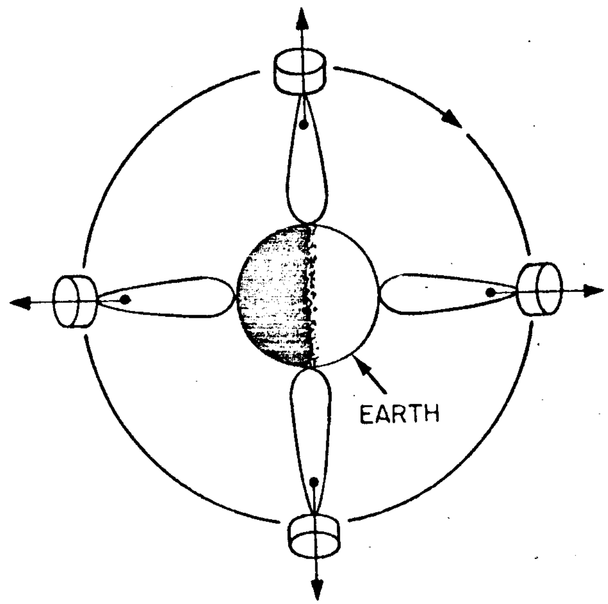
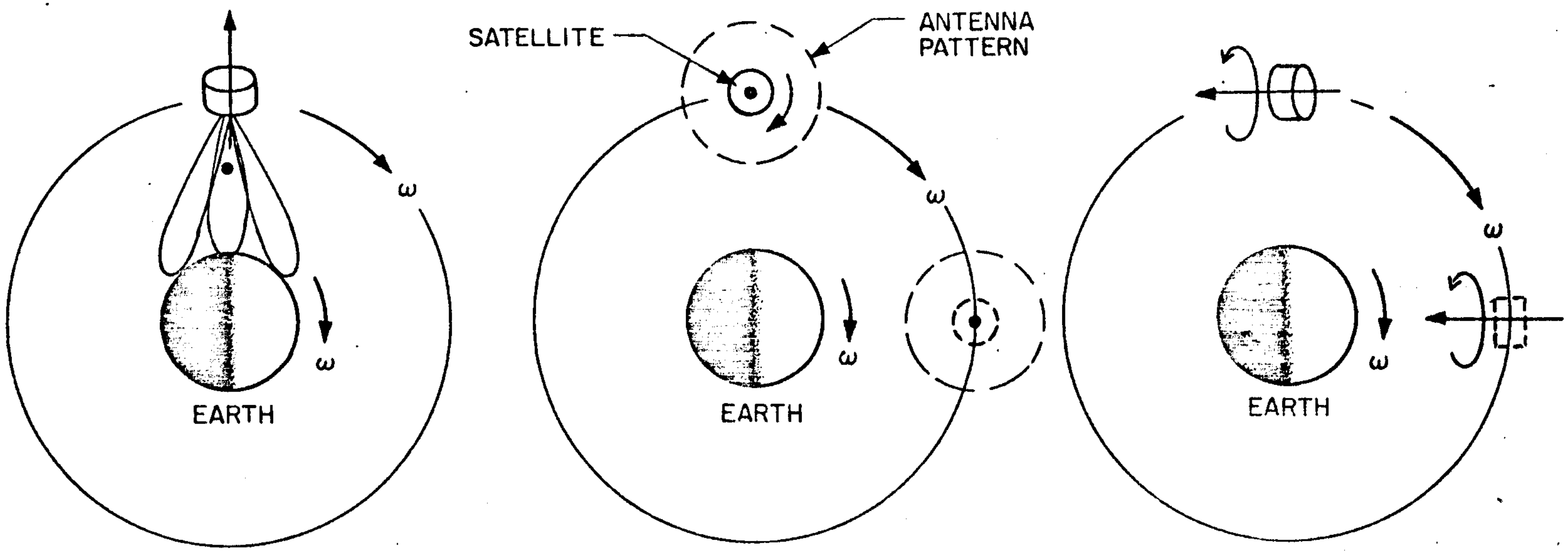


Figure 6–Gravity Gradient Satellite



(a) Gravity gradient

(b) Spin stabilized axis normal to orbital plan

(c) Spin stabilized axis in plan of orbit

Figure 7—Synchronized Satellite

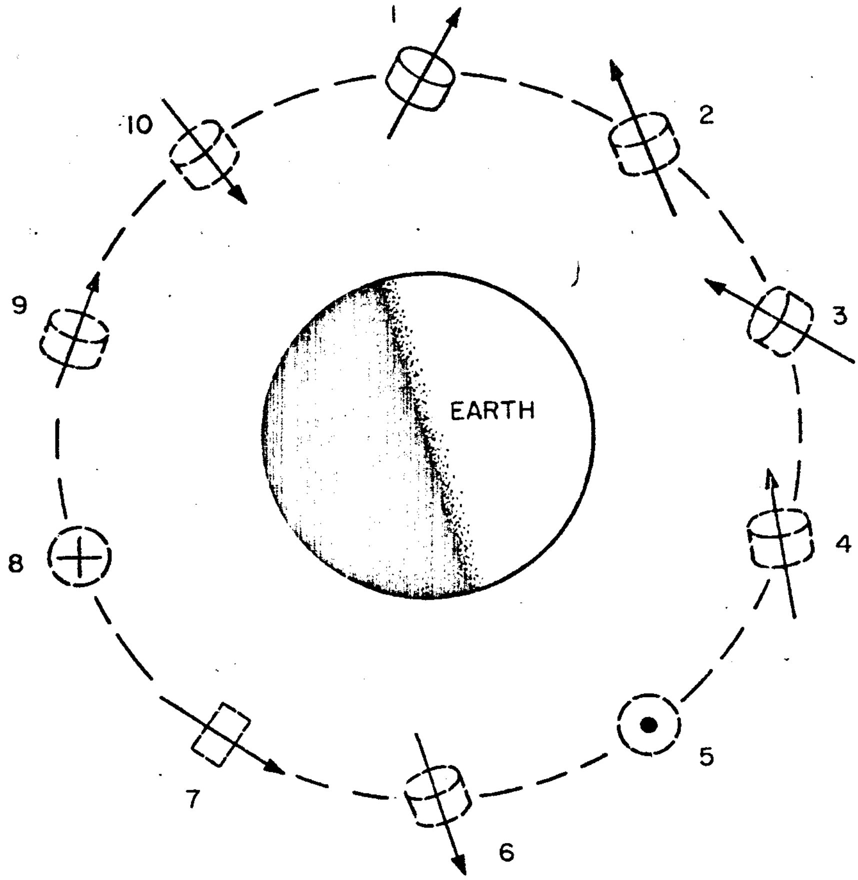


Figure 8–Random Orientation Satellite

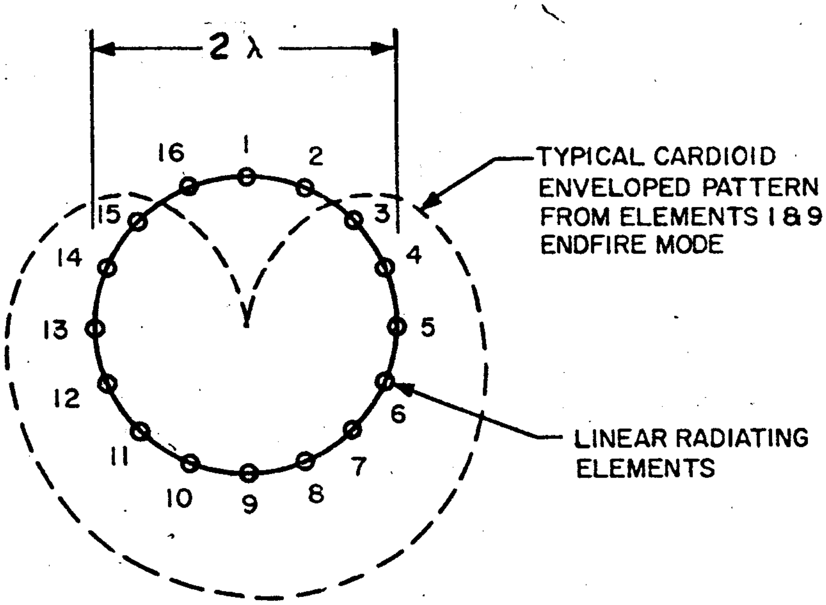


Figure 9 — Hughes Satellite Array (Plan View)

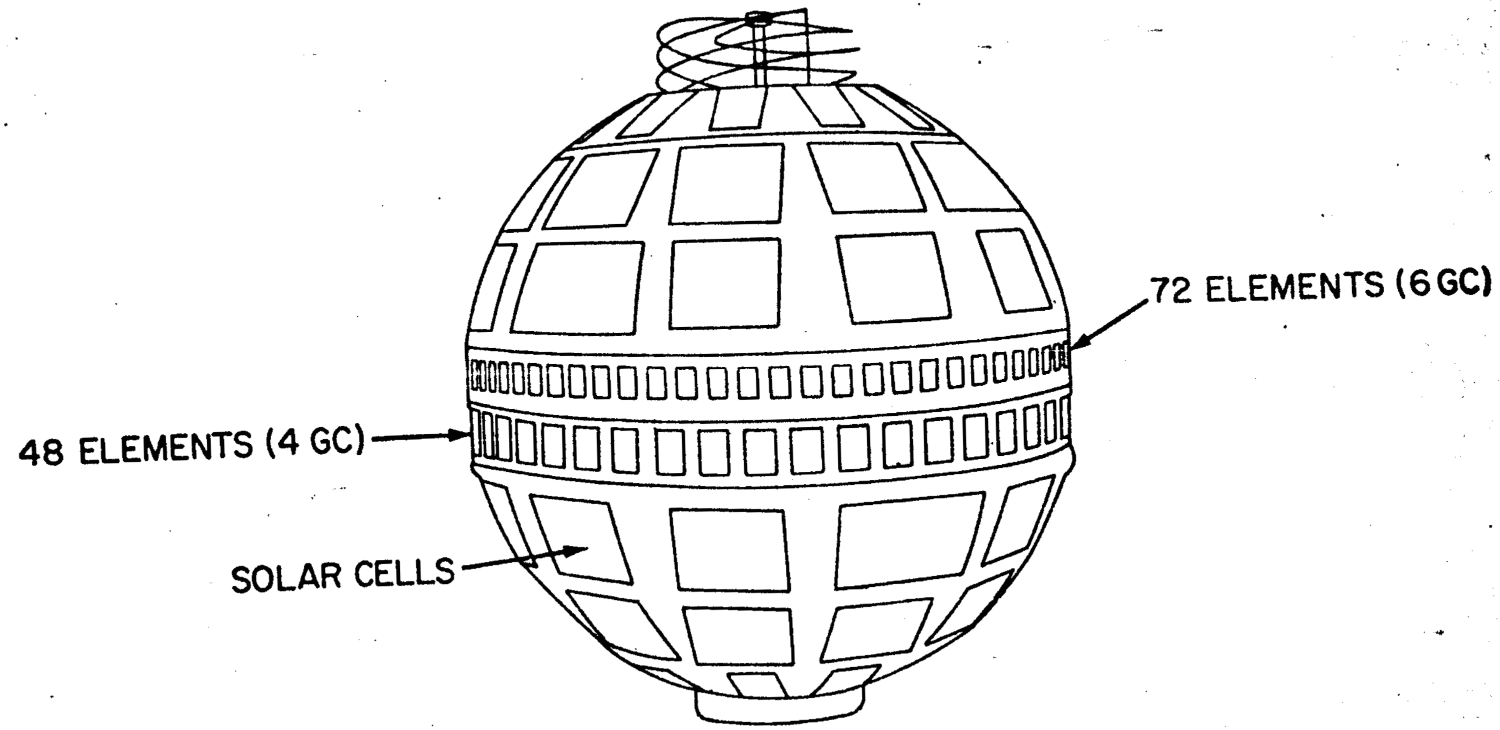
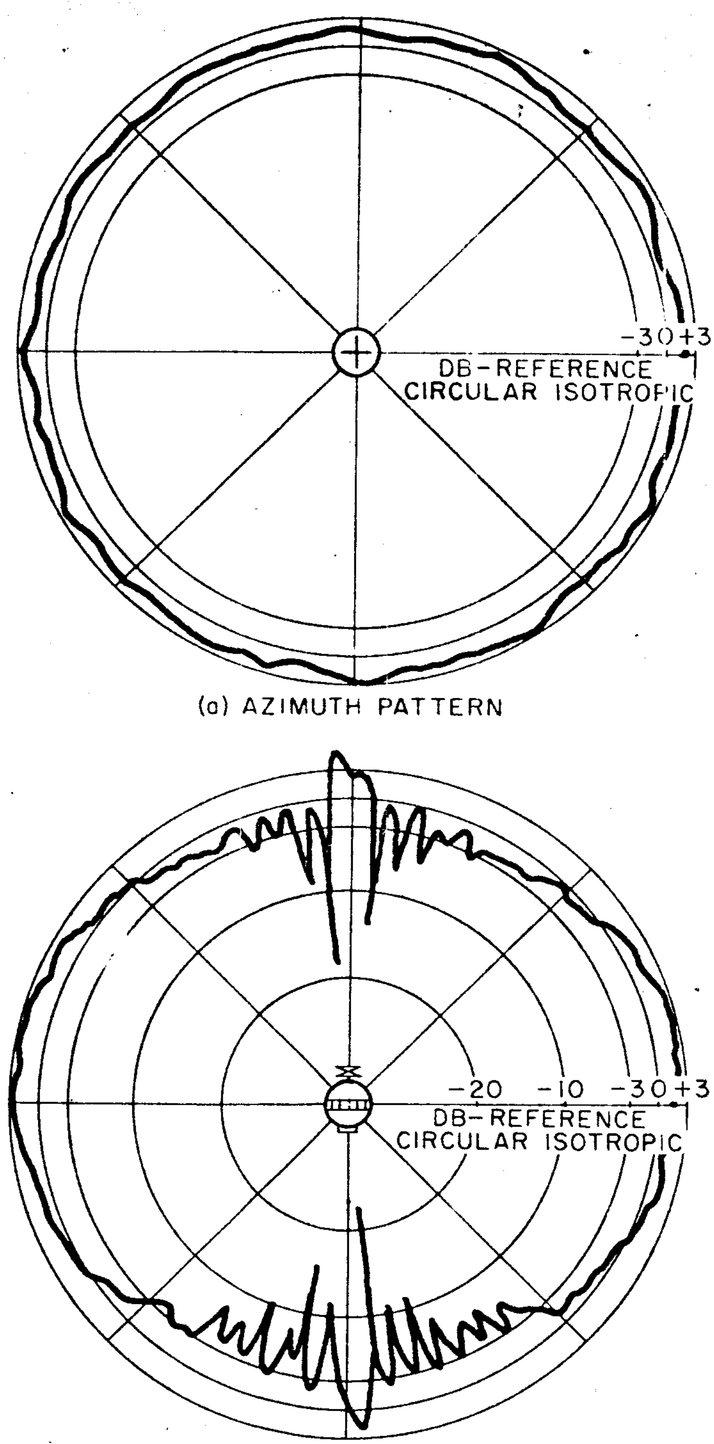


Figure 10—Telstar I



(a) AZIMUTH PATTERN

(b) ELEVATION PATTERN

Figure 11—Typical Pattern of Multi-Slot Belt Array

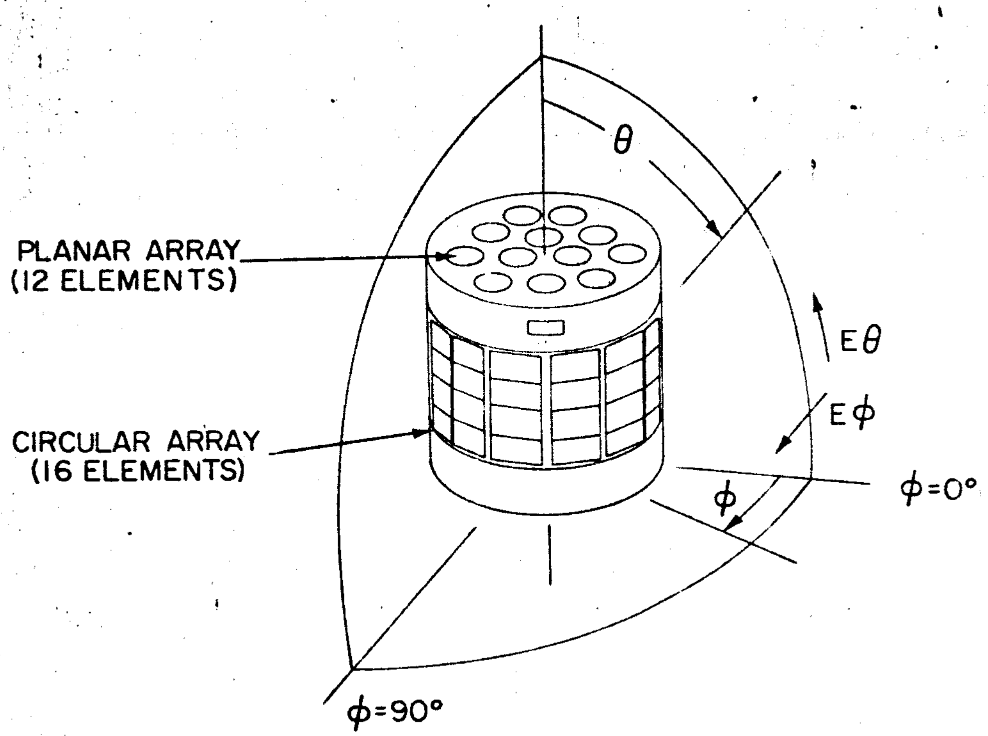


Figure 12a—Coordinate Systems and Array Geometry

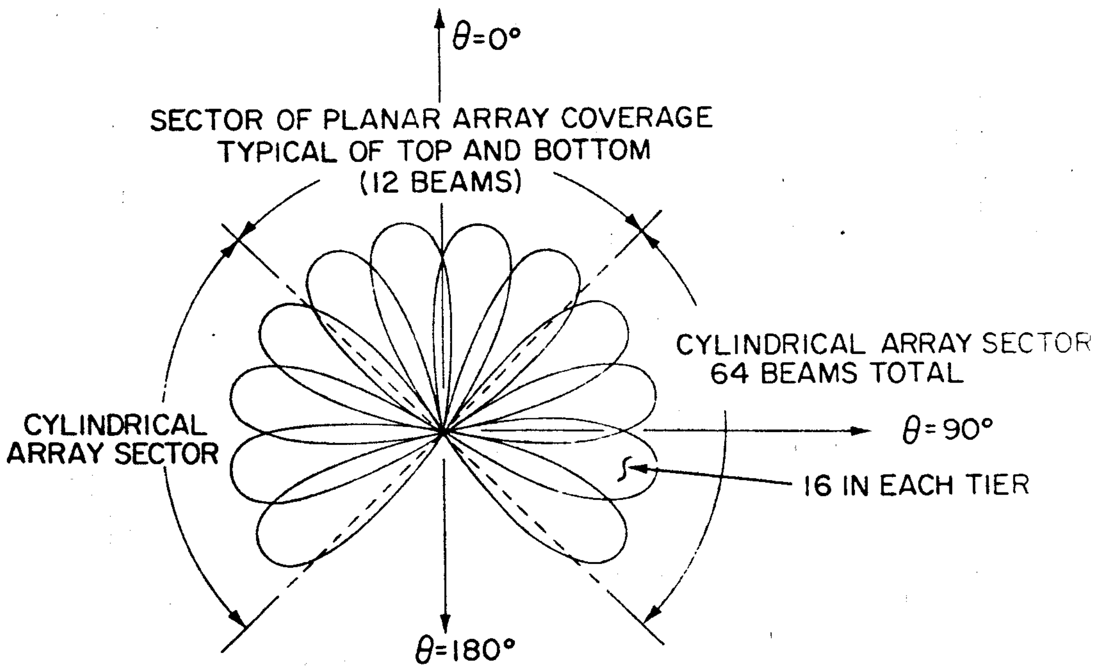


Figure 12b—Disposition of Multiple Beams

Figure 12—Beam Pointing Orientation

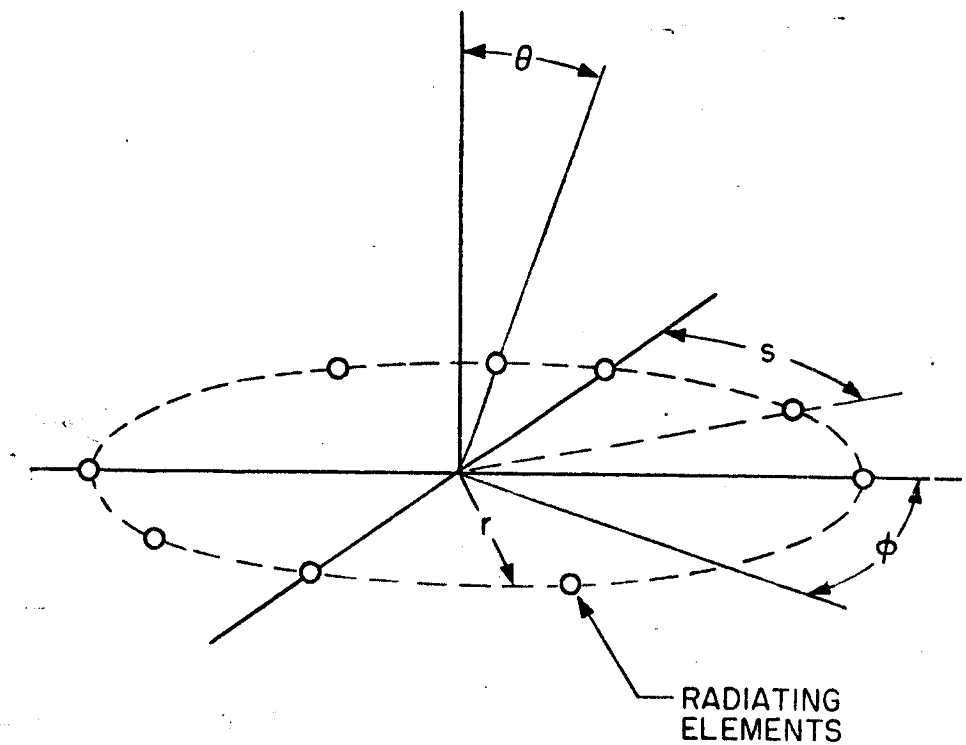


Figure 13 - Basic Geometry and Coordinate System of the Cylindrical array.

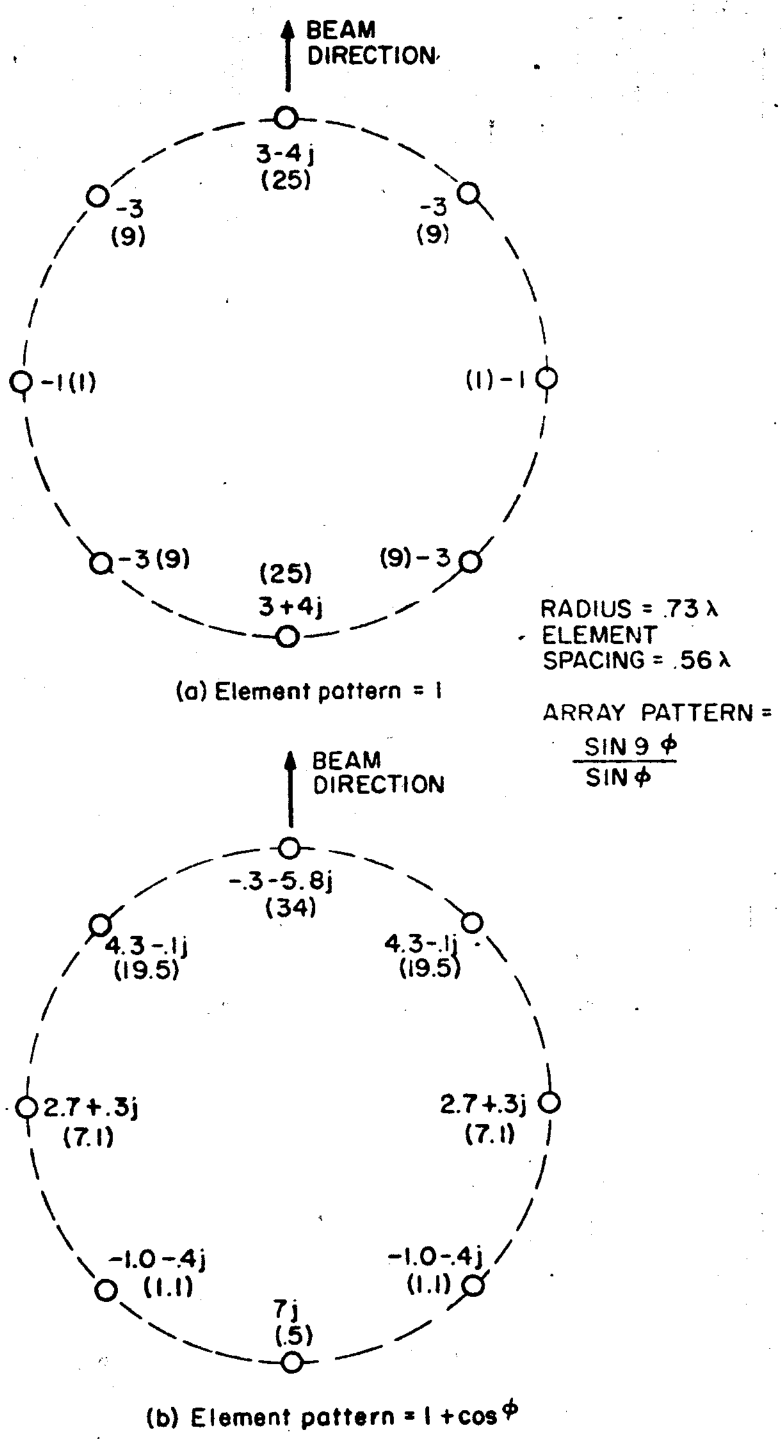


Figure 14 - Element Amplitudes and (Powers) for Two Types of Element Pattern

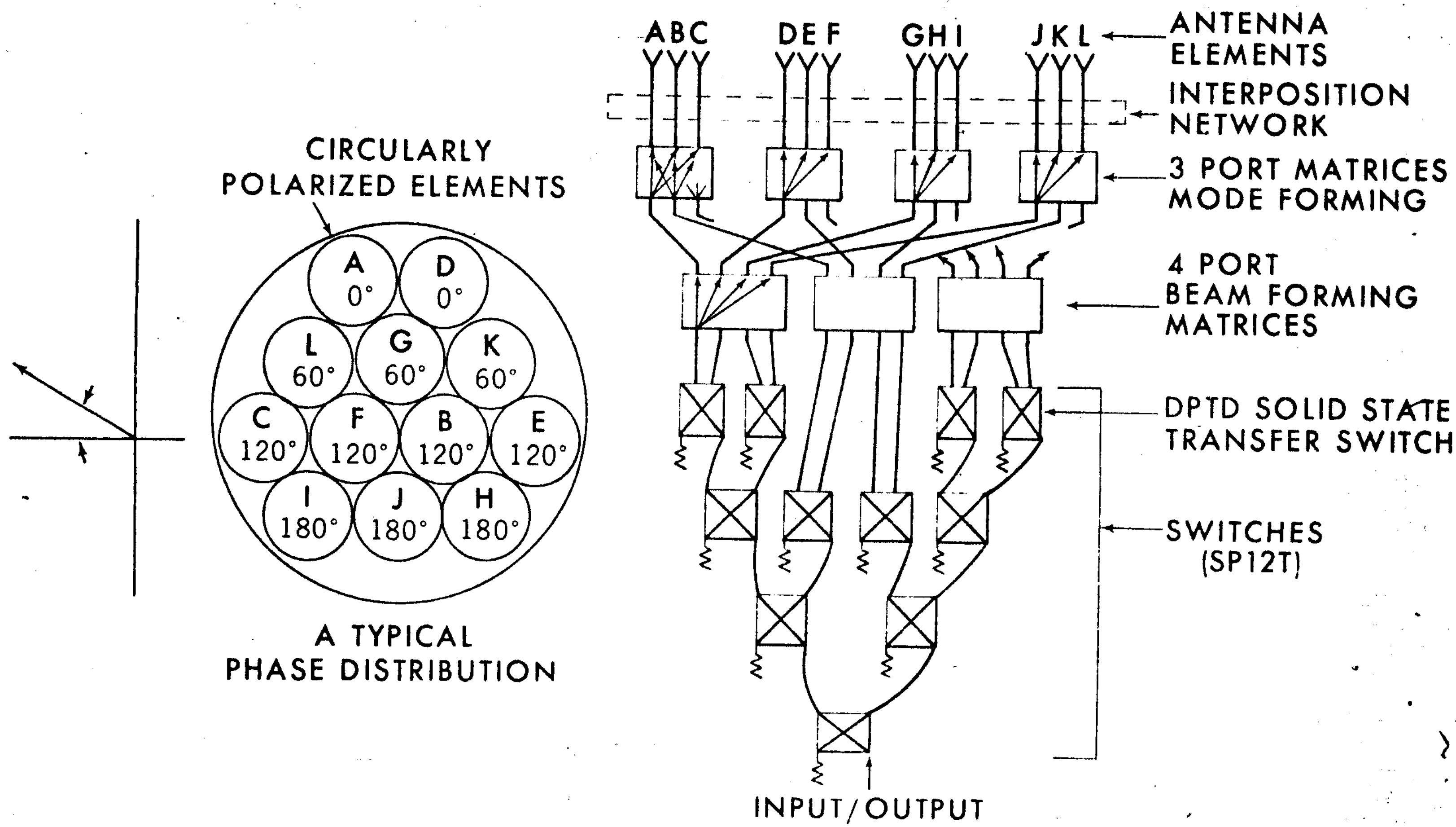


Figure 15 - Planar Array - Circular Aperture

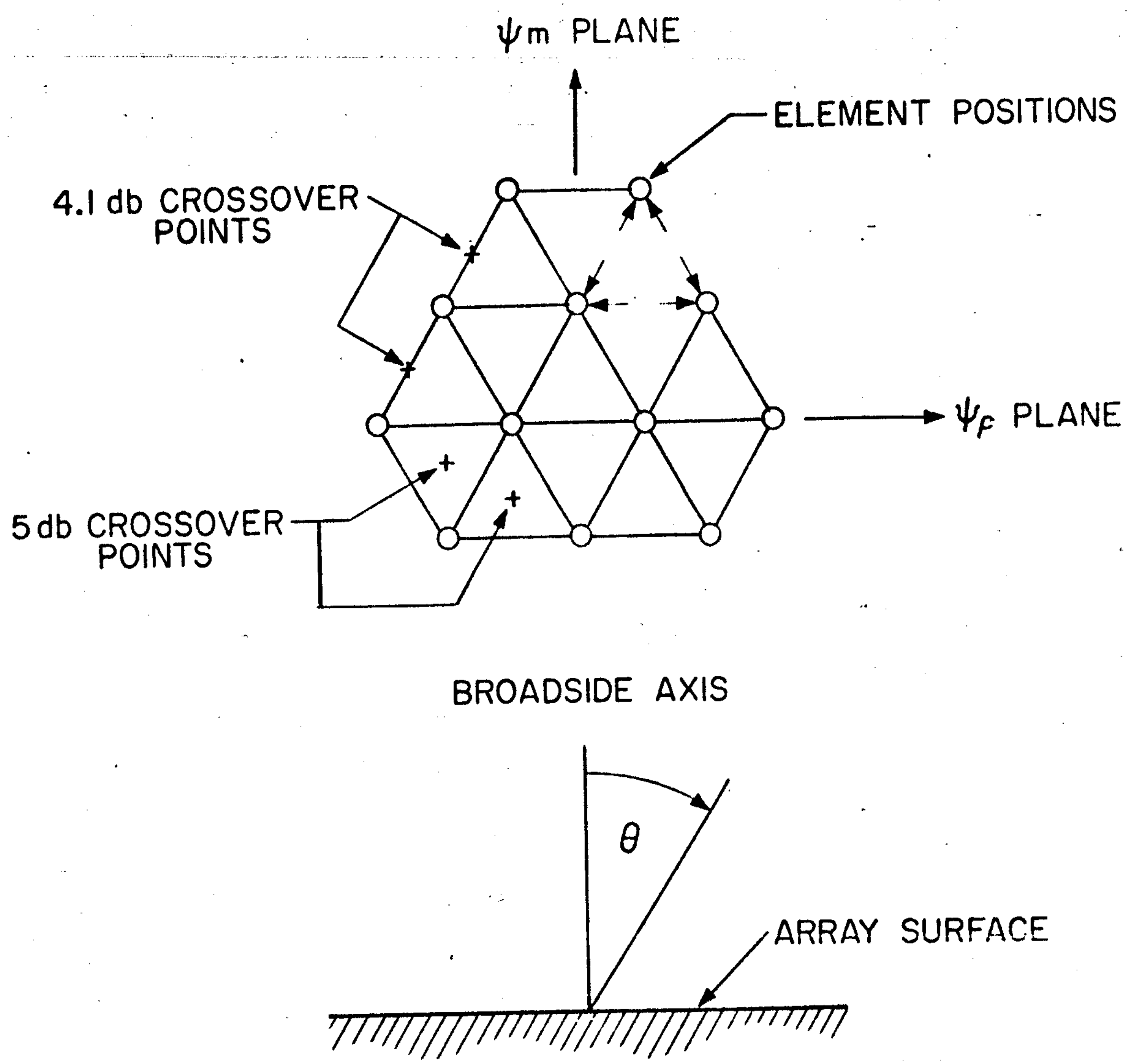


Figure 16-Geometry of the Twelve-Element Array.

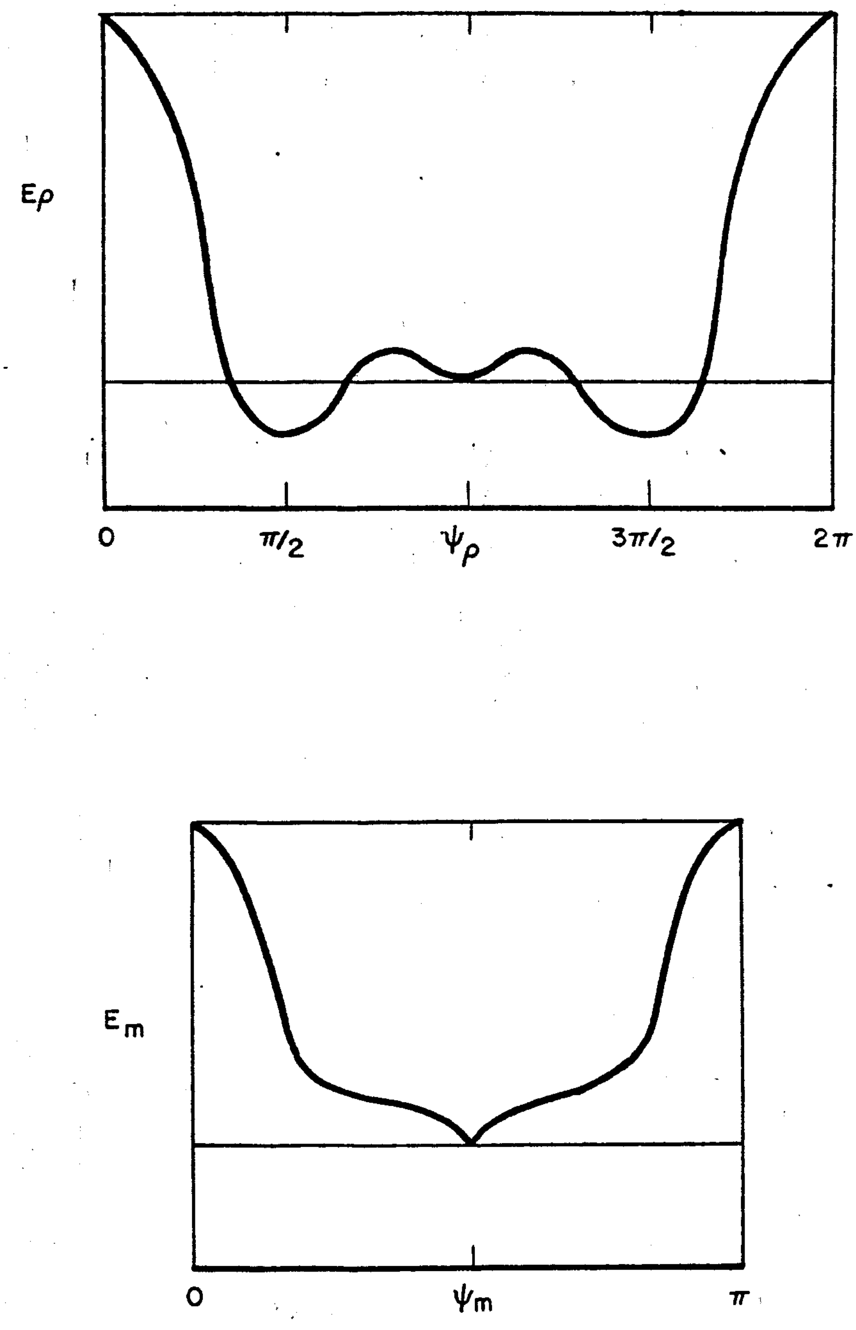


Figure 17 — Array factors for the twelve-element array

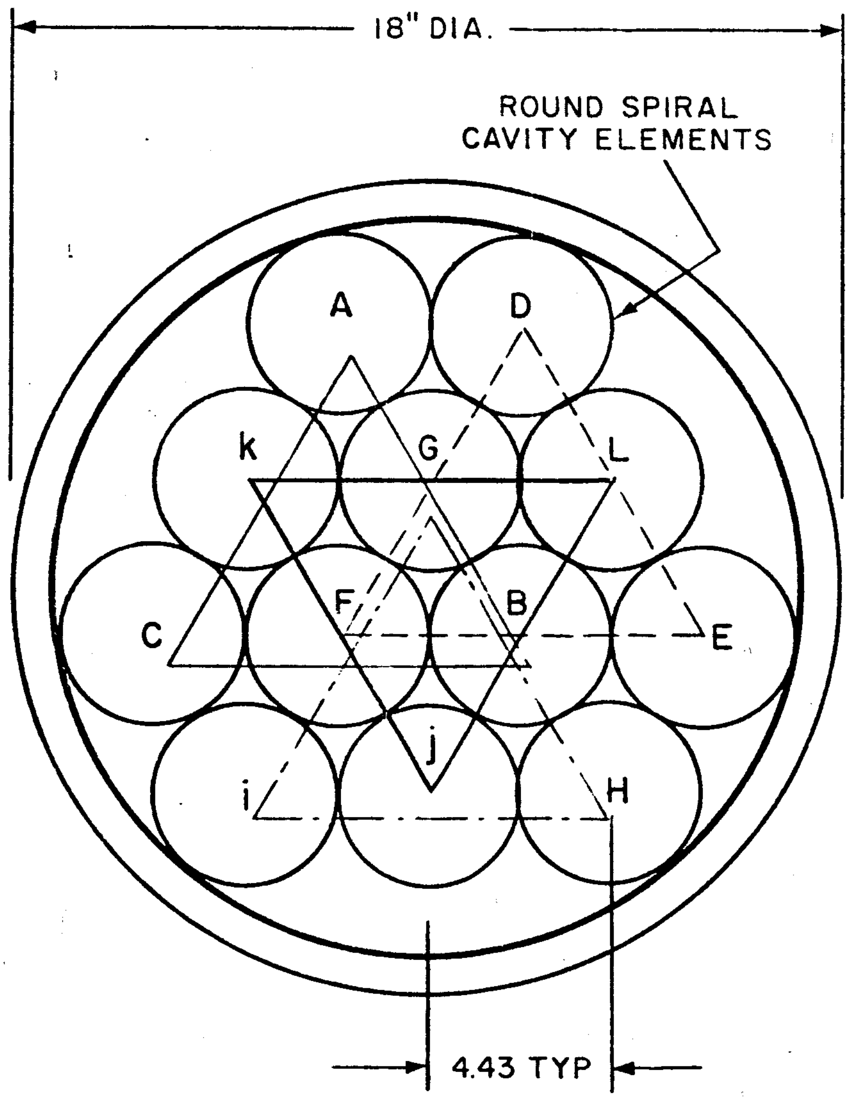


Figure 18— Geometry of the Actual Twelve-Element Array.

RSi

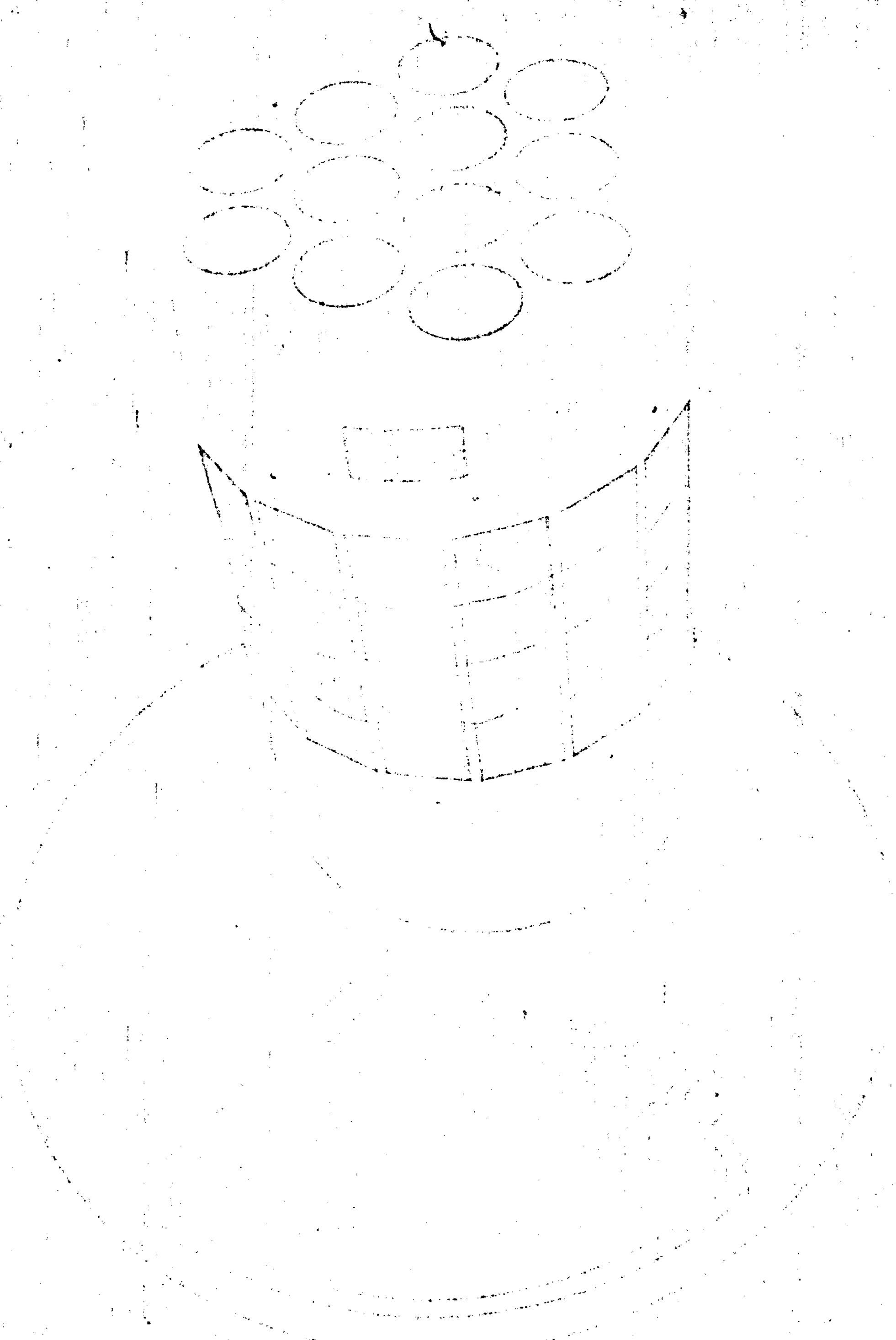


Figure 1 ~~The planar cylindrical multiple beam antenna system~~.
ENGINEERING MODEL– MULTIPLE BEAM PHASED ARRAY

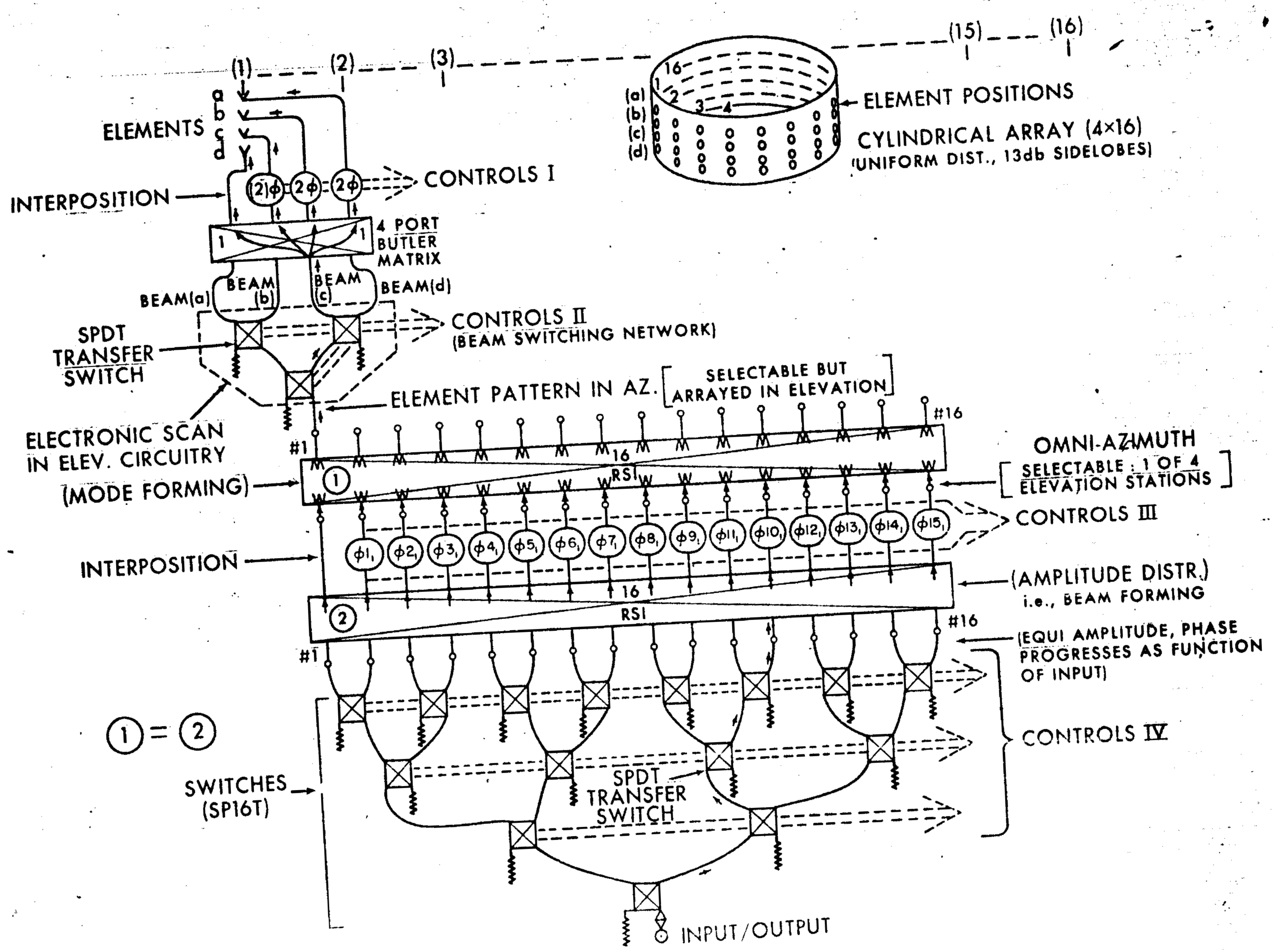


Figure 19 - Cylindrical Array

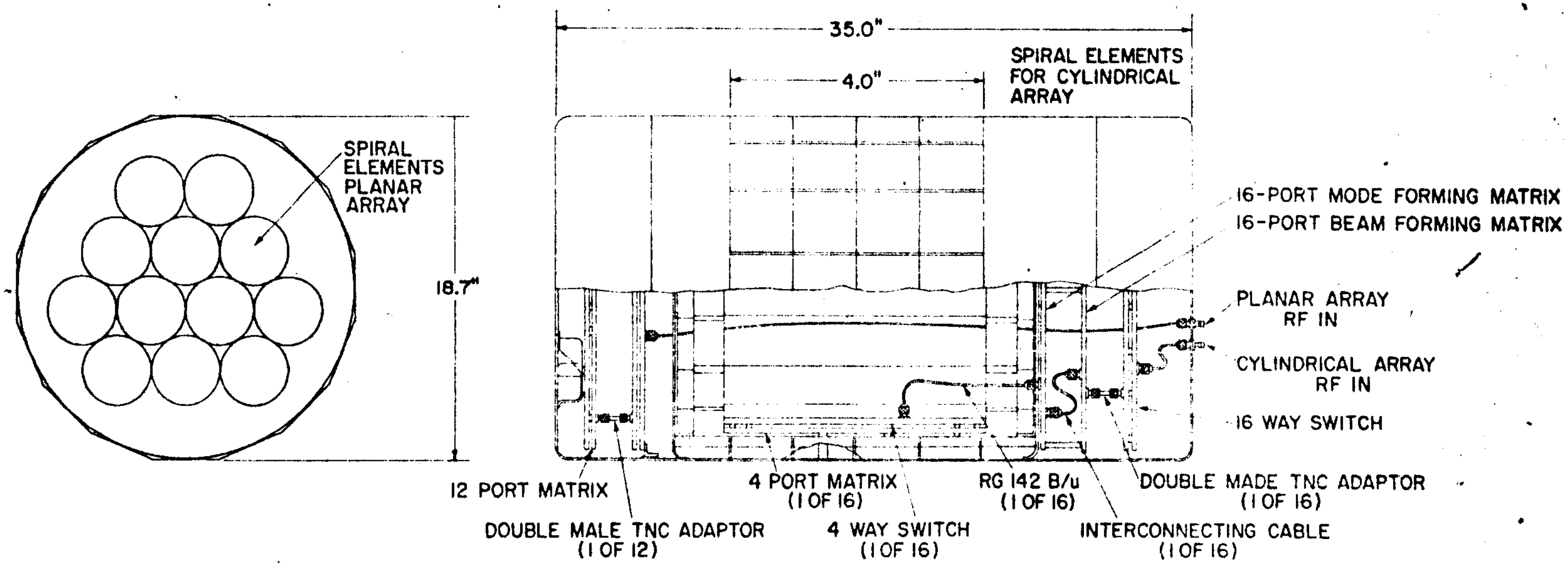


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Figure 20 - Antenna System Package